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A Frequency-Reconfigurable Antenna Architecture using Dielectric Fluids

Mustafa Konca, *Graduate Student Member, IEEE*, and Paul A. Warr

***Abstract*— A new frequency-reconfigurable antenna architecture is presented, in which a dielectric fluid is pumped into a cavity behind the antenna in order to change its resonant frequency. The continuous tuning provided by the changing fluid volume allows the resonant frequency to be adjusted to any value within the tunable range. This tuning method does not affect the power handling capability of the antenna and does not consume power while the resonant frequency is kept constant. This method of tuning also stands out in its class by offering a wide tuning range, high efficiency and very good electrical isolation between the antenna and the control circuitry. The antenna was designed and optimized using Ansys HFSS software and several prototypes were built and tested. Measured results of the input response, radiation pattern and efficiency are presented. Castor Oil (ε_r=2.7) and Ethyl Acetate (ε_r=6) were used in physical tests as the tuning fluids to verify the simulated results. Good agreement between simulated and measured results was observed which is also in line with the behavior suggested by theory and earlier investigations.**

***Index Terms*— Frequency Reconfigurable Antenna, Tunable Antenna, Liquid Dielectric, Fluidic Antenna.**

I. INTRODUCTION

As the demand for high performance communication systems increases, the use of reconfigurable antennas for future commercial applications is emerging. In most situations, using reconfigurable antennas can enhance the performance of a communication system by providing pattern, polarization and/or frequency diversity. In this paper we present a new antenna architecture exploiting the effects of dielectric fluids to achieve frequency tuning.

Many different methods and architectures have been utilized to build frequency-reconfigurable antennas [1]-[5]; most of these employ switches, varactors or some type of mechanical mechanism to change the resonant frequency. Papers [6]-[8] utilize conductive fluids to form flexible and tunable antennas. However the presented antenna is most closely related to the group which exploits the dielectric properties of materials for tuning [9] - [22]. This group includes systems with tunable substrates and artificial dielectric fluids. The effects of having different dielectric materials in proximity to an antenna are well known and documented [23] - [29]. Although these effects can be used to achieve frequency tuning, there are some drawbacks such as decreased efficiency and radiation pattern distortion. Papers [21] and [22] take approaches similar to the presented method, making use of dielectric fluids.

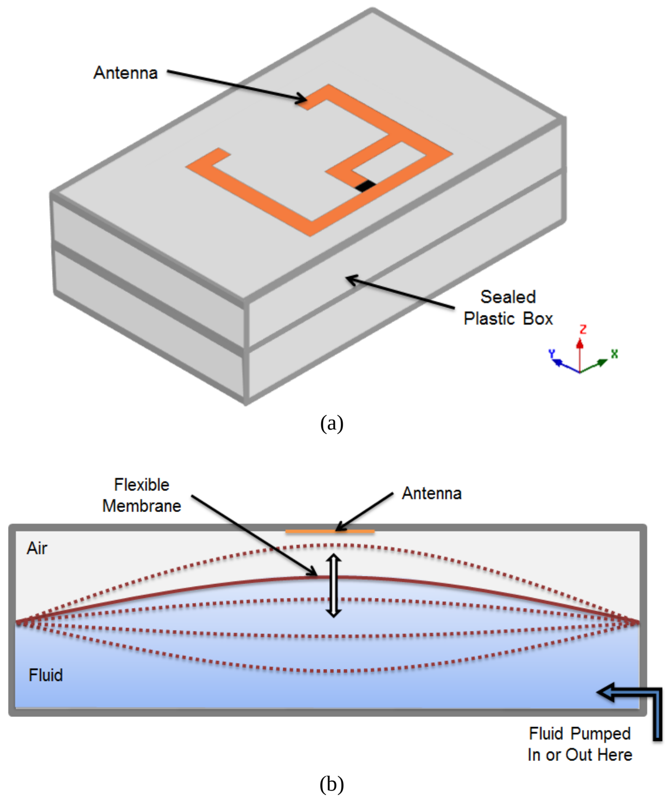

Fig. 1. Illustration of the antenna prototype: Outer view is shown in (a), the antenna is visible but actually resides on the inside face. A cut-section view of the x-z plane is shown in (b), with the hatched lines showing the different shapes that the membrane can take as the liquid is pumped in and out of the enclosure. Air is present in the part of the box that is not taken up by the fluid.

In [21], a body of fluid was used as a dielectric resonator (DR) and the height of the fluid body was adjusted to tune the resonant frequency. A tuning range of around 40% was achieved using this method. No radiation pattern and efficiency information was reported because the antenna could not be rotated in an anechoic chamber due to the lack of a containment apparatus for the fluid.

In [22], fluidic channels were constructed on a circular annular slot antenna and filled with different fluids to achieve tuning. This specific arrangement allowed independent control over the two resonant modes of the antenna by using two fluidic

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The authors are with the Department of Electrical and Electronic Engineering, University of Bristol, BS8 1UB, Bristol U.K. (e-mail: M.Konca@bristol.ac.uk; Paul.A.Warr@bristol.ac.uk).

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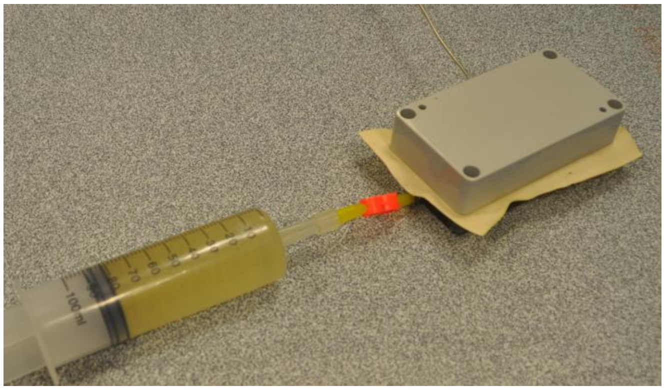
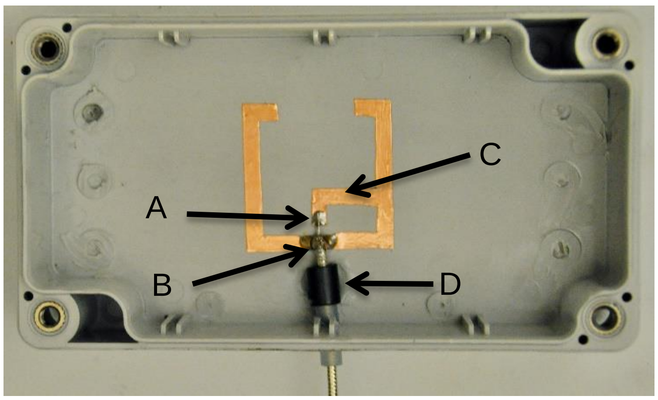
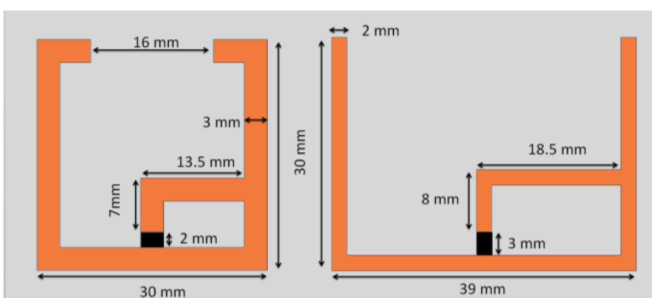


(a)



(b)



(c)

Fig. 2. (a) The top view of antenna enclosure and syringe. The latex membrane which keeps the fluid in place is also visible. (b) The internal view of the antenna. The feeding arrangement can be seen in detail, where the inner conductor is soldered at point A, the coax shielding is soldered to the base of the antenna at B, the gamma match section is indicated by C. A ferrite bead is used to stop any unbalanced currents flowing down the cable at point D. (c) Dimensions of the two bent dipole antennas. The antenna on the left is used with castor oil and the right one is used with ethyl acetate. The antenna is cut out of thin copper sheet and fed over the gap which is shown as a black region.

channels. Water, acetone and air were used as the tuning fluids, providing tunable ranges of 32% and 55% for the two resonant modes. Again, no efficiency figures were given and the effect of the fluid on the radiation pattern was not investigated. In contrast to the presented method, this method does not provide continuous tunability.

Frequency tuning can also be achieved using materials with controllable electrical properties. Some examples such as BST (Barium-Strontium-Titanate), YIG (Yttrium Iron Garnet) and liquid crystals can be made into thin electromagnetically tunable substrates [3], [9] - [18]. Artificial fluids with controllable electrical properties are also proposed [19], [20]. These are usually designed by suspending a chosen amount of particles in low-permittivity oil.

In the presented system, a fluid dielectric is pumped in or out of a cavity behind an antenna in order to change the resonant frequency. An illustration of the proposed antenna design is shown in Fig. 1. This architecture comprises a planar antenna placed over a cavity, initially containing air which is then filled with a fluid to tune the operating frequency. The fluid is constrained by a flexible membrane at the upper boundary. This keeps the system sealed and limits the shifting of the fluid as the antenna is moved or positioned in a different orientation. Limiting the movement of fluid minimizes the variation in the antenna's performance, which is significantly affected by the shape and proximity of the liquid body. The fluids used in our physical tests are castor oil and ethyl acetate with relative permittivity values of 2.7 and 6 respectively.

The main advantages of the presented method are continuous tunability, high isolation from the control circuitry and high power handling capacity. Results are presented for a narrow-band antenna; nevertheless, this tuning method can also be used with other types of antennas.

II. The Prototype

A. Enclosure

The sealed plastic box, as seen in Fig. 2 (a), is comprised of an ABS (Acrylonitrile Butadiene Styrene) body and clear polycarbonate lid, both with a relative permittivity of around 2.7. It is important to choose an enclosure with a low permittivity and low loss to maximize the tuning range and maintain efficiency. The outer dimensions of the box are 120 mm by 65 mm by 40 mm with 3 mm thick walls. A flexible diaphragm, made of 1 mm thick latex rubber sheet, is placed across the opening of the box. The fluid is pumped in from the polycarbonate side and bound by the diaphragm. This diaphragm expands as more fluid is pumped into the cavity and eventually touches the top of the enclosure, conforming to the shape of the enclosure at full capacity.

Diaphragms of different thickness were tested and the 1 mm thick latex was found to be optimal as it was firm enough to hold the fluid firmly and thin enough to not affect the antenna performance.

B. Antenna

The utilized antenna design is a bent half-wave dipole with a "gamma match" style feed [30], [31]. Full-wave simulations showed that antenna dimensions should be optimized for a given dielectric fluid in order to maintain the impedance match over a broad tuning range. Fig. 2 (c) shows the antennas used in testing along with the dimensions which ensured that the antennas were well matched at all fluid levels.

The antenna is cut from copper foil and placed on the inside face of the enclosure (on the side made of ABS plastic). The antenna is fed by a coaxial cable which penetrates the side of the box. A ferrite bead placed on the cable is utilized as a choke to stop any unbalanced current flow. The planar form of the antenna and thin coaxial feed cable does not disturb the diaphragm as it expands. A detail-view is provided in Fig. 2 (b)

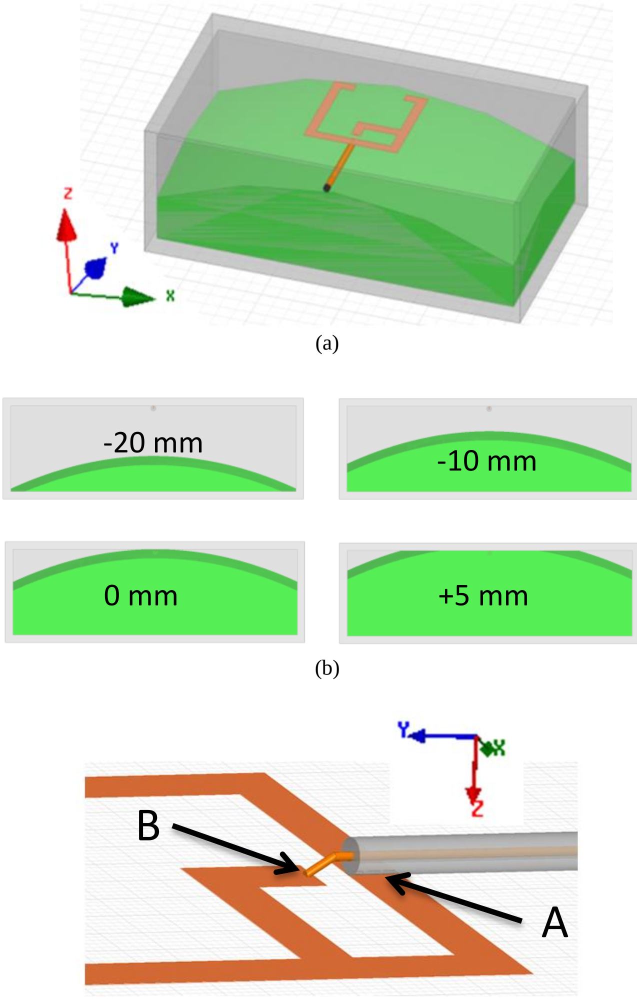


Fig. 3. HFSS model of the bent dipole antenna: (a) Shown with the box (semi-transparent) and the fluid (green). (b) Side view of the antenna model illustrating the fluid curvature model at different fluid heights. The diaphragm is shown at different heights: -20 mm, -10 mm, 0 mm (tangent to the antenna) and +5 mm (top of the diaphragm flattens as it touches the antenna). (c) Detail view of the coaxial feed arrangement. The sheath of the coaxial cable is soldered to the base of the antenna at point A and the inner pin is connected across the gap to the bent feed section at point B.

Other antenna types such as a bowtie and a planar dipole were also tested and successfully tuned. However, the selected antenna was chosen for the demonstration of the dielectric effects because it has a single and strong resonant point. On the other hand, some antennas exhibit a change in their mode of resonance as the fluid level changes.

C. *Pumping mechanism*

A 100 ml syringe is used for measuring and pumping the dielectric fluid. This is connected to the polycarbonate part of the enclosure using silicone tubing and fed through a brass nipple. A plastic pinch-valve is placed on the silicone tube to stop the flow of fluid during measurements.

D. *Dielectric Fluids*

In choosing the fluids for the practical measurements, the main parameter is their relative permittivity. Simulation tools can be used to design an antenna that has a stable mode of operation at all levels for a given fluid. However, this process becomes more challenging as the permittivity of the tuning fluid increases. This is because the antenna is detuned more severely and matching into air becomes harder around high permittivity materials.

Furthermore, the chosen fluids has to be non-hazardous, easy to handle, easily obtainable and non-reactive. Castor oil with a relative permittivity of 2.7 is used in many different electrical applications but it has a high loss tangent at the frequencies of interest [32]. Ethyl acetate reacts lightly with ABS and polycarbonate materials but it is a desirable fluid due to its low loss and relative permittivity value of 6 [33], [34]. The part of the box in contact with this fluid is covered with a layer of epoxy to prevent degradation of the box and contamination of the fluid. The membrane does not require any treatment since latex is very resistant to ethyl acetate.

III. Simulation and Measurement Results

In this section, simulated and measured results of the resonant frequency, radiation pattern and efficiency of the proposed antenna are presented. The results are given for variations using different fluids with varying amounts of fluid in the system.

The 3D model differs from the actual prototype in the curvature and shape of the diaphragm. The diaphragm in the prototype is fixed around its perimeter and expands symmetrically about z, eventually embracing the whole inner surface of the box on the ABS side. This type of a shape cannot be modelled easily using a simple parameter which would be swept to tune the antenna. Due to this difficulty, the fluid body is modelled as a curved volume which fills the box as it moves along z (Fig. 3(b)). The difference in the shape of the fluid body does not permit a one-to-one comparison between the measured and simulated results at intermediate points. A direct comparison can be made when the box is completely full or completely empty. Between these two points similar trends are observed in simulations and measurements.

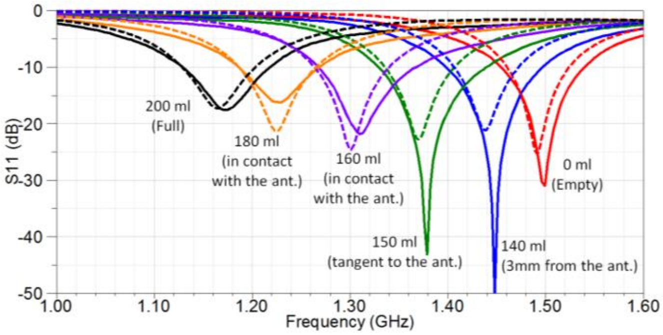
The “volume of the injected fluid” is used as the independent variable for the measured results. However this volume does not correspond to the volume obtained in simulations, because the curved surface used to model the shape of the diaphragm is an approximation. Due to this incompatibility, the variable used in the simulations is the “distance of the fluid body from the antenna”. The 3D model used in the simulations can be seen in Fig. 3.

In the simulations, the loss tangent of the castor oil is taken as 0.1 and the ethyl acetate has a frequency dependent loss tangent which is 0.022 at 0.9 GHz, 0.055 at 1.2 GHz and 0.045 at 2.45 GHz.

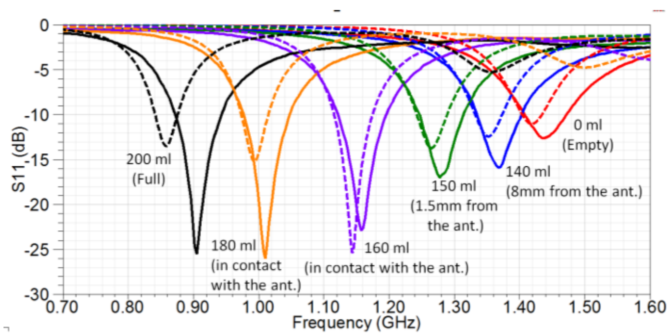
A. *Input Response*

In the first step of the physical measurements, the antenna was tested on the box with no fluid. Then, castor oil was injected into the system in 10 ml increments and the input response recorded (only 6 plots are presented for clarity). This process was repeated for ethyl acetate using the second antenna.

Measured and simulated input response plots for both fluids



a) Castor Oil



b) Ethyl Acetate

Fig. 4. The simulated (dashed lines) and measured (solid lines) input response of the antenna presented at different fluid levels: The volume of the injected fluid or the distance between the fluid and the antenna is shown next to the corresponding curves on each plot.

are given in Fig. 4. The measurements show that the first antenna (optimized for castor oil) resonates at 1.50 GHz while the box is empty. The introduction of the castor oil reduces the resonant frequency of the antenna as expected. Using castor oil, the resonant frequency can be tuned between 1.17 GHz and 1.50 GHz, giving a tunable range of 25%. The simulation results are similar with a tunable range between 1.14 GHz and 1.49 GHz.

The second antenna (optimized for ethyl acetate) resonates at 1.44 GHz while empty. With the introduction of the ethyl acetate, the resonant frequency reduces to 0.9 GHz, providing a tunable range of 46%. Simulations of this configuration give a tunable range between 0.86 GHz and 1.42 GHz. The range of differences are easily within simulation and realization tolerances.

Calculations using the measured data indicate that the effective permittivity around the structure is increased by a factor of 1.68 using castor oil and 2.60 using ethyl acetate.

The antenna maintains its -10dB impedance bandwidth reasonably well as the fluid level changes. There is no noticeable change in the response as the antenna is rotated or moved, indicating that the diaphragm holds the fluid tightly enough to limit the movement of fluid in the box. The accuracy of the simulations allowed for the final prototype to be realized without any iteration or modification to the antenna structure.

B. *Radiation Pattern*

The radiation pattern of the antenna was measured in an anechoic chamber at six different fluid levels ranging from empty to full with both fluids. As the prototype antenna radiates

TABLE 1
MEASURED RADIATION EFFICIENCY

Injected Fluid Volume	**Castor Oil**		**Ethyl Acetate**	
	Resonant Frequency	Radiation Efficiency	Resonant Frequency	Radiation Efficiency
Empty	1.50 GHz	90%	1.44 GHz	92%
140 ml	1.45 GHz	64%	1.37 GHz	69%
150 ml	1.38 GHz	60%	1.28 GHz	73%
160 ml	1.31 GHz	58%	1.16 GHz	75%
180 ml	1.23 GHz	54%	1.01 GHz	80%
Full	1.17 GHz	47%	0.90 GHz	82%

in all directions, one would expect the accuracy of the radiation pattern measurements to be affected by reflections from the mounting assembly. This would not be the case with a more directive antenna such as a microstrip patch. Nevertheless, knowing the exact radiation pattern is not a primary concern; the main goal is to observe the differences in performance at different fluid levels. The 3D radiation patterns obtained from the measurements are given in Fig. 5.

Earlier work on the effects of dielectric coatings and radomes shows that dielectrics in close proximity to an antenna can cause distortion to its radiation pattern [23] - [27]. For the presented antenna design, it is reasonable to expect the radiation pattern to be similar at different fluid levels as long as the mode of excitation does not change.

The results show that the addition of the dielectric fluid causes some distortions in the radiation pattern. The radiation pattern is most significantly affected in the z-direction, where the intensity varies by about 10dB. Although, there are variations at other areas, they are smaller, hence the pattern stays similar in character. It is apparent in Fig. 5 that the radiated power increases in the z-direction (0 degrees on the 2D plots) as the fluid level rises. Possible causes for this effect are the denser field in the high permittivity areas (lensing effect) and reflections from the fluid boundary.

The simulation software is not very reliable for radiation pattern results, especially when the antenna structure is not simplistic. Nevertheless, the trend of rising radiation along the z-axis as the fluid level increases was also observed in the simulations.

Some other tunable antenna systems excite higher modes in the process of tuning which cause severe changes in the radiation pattern. Pattern variations commonly cause unwanted changes in the characteristics of a communication system. The presented method provides a more stable pattern provided that care is taken in the antenna design process to avoid changes in the resonant mode as the antenna is tuned.

C. *Efficiency*

Efficiency figures were measured at different fluid levels to ascertain the fluid's effect on the antenna performance. The radiation efficiency of the antenna was calculated by comparing its total radiated power to that of a reference monopole. In order to obtain this figure, the monopole was tuned to the same operating frequency as the test antenna and both antennas were

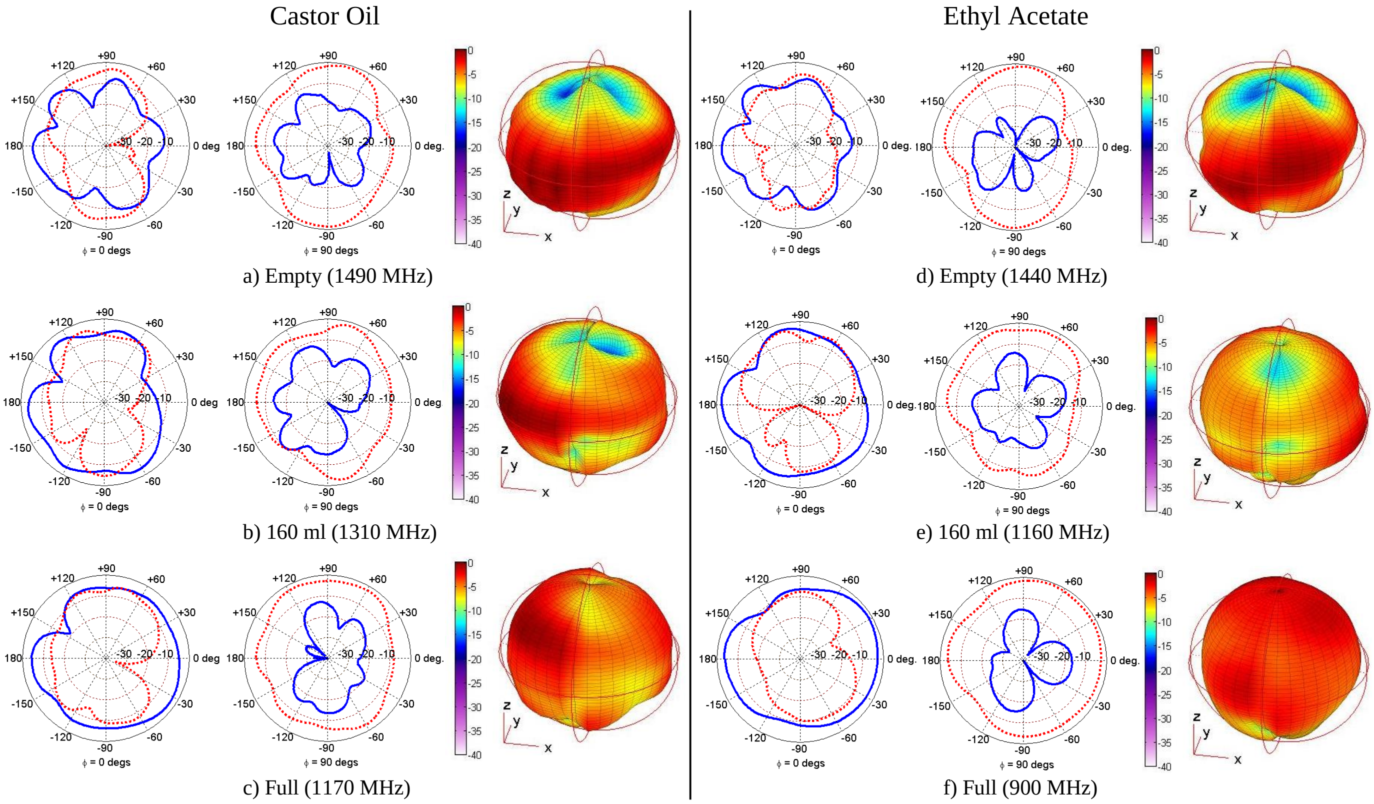


Fig. 5. Measured total power radiation patterns (directivity) given in dB scale for both antennas with different volumes of fluid: The measurements were carried out at the corresponding resonant frequency for each case. Each plot is normalized to the maximum directivity obtained in that measurement. In the 2D plots, zero degrees corresponds to the positive z direction on the 3D plots. The solid blue lines show the E-theta pattern and the dashed red lines represent the E-phi pattern.

measured in succession. The measured results of the radiation efficiency are summarized in Table 1.

Using castor oil, a decrease in efficiency is seen with increasing amounts of dielectric fluid as expected. This effect is heightened because the fluid lowers the resonant frequency of the antenna and castor oil has a higher loss tangent in this region [32]. The relative decrease in efficiency is about 48% after filling the enclosure completely with castor oil.

Using ethyl acetate, a more complex efficiency trend is observed. The lowest efficiency figure (69%) is obtained when the cavity is partially filled. As more fluid is added, the efficiency increases up to 82%. This is because the loss tangent of ethyl acetate is lower at this frequency [33, 34]. The relative drop in efficiency was about 25% at its worst using ethyl acetate as the tuning fluid.

Simulated efficiency data agrees with the presented results for the frequencies with a known loss tangent. For ethyl acetate, the data from [33] indicates a loss tangent of 0.022 at 900 MHz and 0.045 at 2.45 GHz; another source [34], provides a loss tangent of 0.052 at 1.2 GHz. For the empty state (1.44 GHz), the measured efficiency is 92% and the simulated efficiency is 94%. At 1.16 GHz (tan δ: 0.052) the measured efficiency is 75% and the simulated efficiency is 73%. When the box is full (tan δ: 0.022 at 900 MHz), the measured efficiency is 82% and the simulated efficiency is 81%. For other points, the simulated efficiency figures are not presented as they depend on our estimations and extrapolations of existing loss tangent data.

IV. Further Work and Pathways to Applications

A. Development from Prototype

The presented prototype was built with readily available materials as a proof-of-concept demonstrator. The size of the system can be reduced by using a more compact, purpose-built enclosure and a micro pump. The smaller cavity would shorten the tuning time but would also slightly decrease the tuning range. Simulations made using a 10mm high box with 1mm thick walls (as opposed to the 40mm high box with 3mm thick walls used for the prototype) showed that 90% of the original tuning range could still be attained.

Current state of the art microfluidics technology could be used to achieve even further miniaturization [35] - [37]. In this case, tuning would be achieved by pumping fluids into cavities etched into the substrate of a patch antenna. Such a level of miniaturization would allow these systems to be used in mobile devices in the form of microfluidic chips. At this scale, the tuning speed would improve significantly due to the lower volume of fluid required, again at a cost of smaller tuning range.

Using fluidic cavities on both sides of the antenna can improve the tunable range greatly at a cost of increased complexity. This idea was not tested or simulated but a similar scenario is presented in [29], where an antenna is surrounded with dielectric media.

Use of artificial fluids with nano-particles or purpose made mixtures with low loss but high permittivity could also improve the performance of the system. The presented results clearly support this notion as the castor oil which is lossy at the frequency of interest results in lower efficiency and the higher permittivity fluid provides a wider tuning range.

While higher permittivity fluids offer the advantage of a wider tuning range, they put stricter constraints on the antenna design; it becomes harder to design an antenna that would be impedance-matched at all fluid levels as the permittivity of the tuning fluid increases.

B. Possible Applications

The presented tuning technique is suitable for use in communication applications that require flexibility in their operating frequency but can tolerate slower tuning. One such application is fixed, point-to-point links where it is desirable to avoid congested frequencies. This type of tuning is especially suited for such high power links as the tuning method does not constrain the power handling capability of the antenna, unlike the tuning methods utilizing circuit elements.

The main properties that make the proposed architecture preferable are continuous tunability, wide tunable range, power handling capability and isolation of the antenna from its tuning circuit. Any application requiring such properties would likely benefit from using the proposed tuning method. More specifically, compared to MEMS switches, the proposed method offers continuous tunability and better power handling. Compared to varactors, it offers higher efficiency, wider tunable range and better power handling. Compared to pin diodes it offers continuous tunability, higher efficiency, better power handling and better isolation.

The recent developments in microfluidic circuits and micro pumps may also allow the presented tuning method to be implemented in larger mobile devices such as laptops. Disadvantages such as slow tuning speed and high cost would make this technology less preferable in consumer-end devices. However, specialized applications requiring continuous tunability and high isolation may benefit from the proposed method.

This tuning technique can also be used in specialized sensing and radar systems, where an antenna needs to be matched into another medium such as ice, sand or rock. The fluid level could be adjusted for different types of media, and the particular local conditions, until a good match is obtained.

V. Conclusion

A new architecture using dielectric fluids for frequency tuning of planar antennas has been presented with simulated and measured results. The employed diaphragm successfully holds the fluid in place resulting in an antenna that is practical to use. Two different fluids were tested using an optimized antenna for each case. Using ethyl acetate as the tuning fluid, a tuning range of 46% was achieved without a significant deterioration in the radiation pattern and a maximum 25% fall in efficiency within the whole range.

The presented method provides continuous tuning and its use is not limited to the type of antenna used in this prototype. This method provides a wide tuning range and high efficiency compared to other methods exploiting dielectric effects for tuning. Other notable advantages of this tuning method are high power handling capability and high isolation from the tuning mechanism.

It has been shown that it is possible to obtain a wide tuning range with a relatively small compromise in antenna efficiency and radiation pattern variation using the presented architecture. The results indicate that it is imperative to choose the right combination of fluid and antenna design to obtain the desired tuning range while maintaining efficiency.

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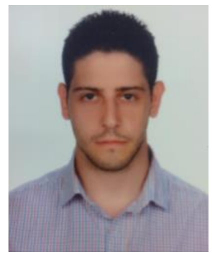

Mustafa Konca (M'05) was born in Famagusta, Cyprus in 1987. He has received his BS (with High Distinction) in electrical and computer engineering from Worcester Polytechnic Institute, MA, USA in 2008 and his MS degree in Electrical and Electronic Engineering from Eastern Mediterranean University in Famagusta, North Cyprus in 2010.

He is currently studying towards his PhD at the University of Bristol, UK on the topic of reconfigurable RF architectures. He has previously worked on a high power RF amplifier project funded by NXP during his undergraduate degree and focused on beam forming antenna array design for his MSc thesis. His research interests include passive RF circuits, reconfigurable antennas, antenna arrays and RF applications of microfluidics.

Paul Warr (Senior Lecturer, University of Bristol) received his PhD in 2001 from the University of Bristol for his work in octave-band linear receiver amplifiers, his MSc in Communications Systems and Signal Processing also from Bristol in 1996 and his B.Eng. in Electronics and Communications from the University of Bath, in 1994.

He has spent periods in the industrial research environment; in Marconi working on communications hub design, and in Phyworks working on analogue IC design. He has over 43 international publications and has filed 5 patents.

His current research covers the front-end aspects of Software (Reconfigurable) Radio and diversity-exploiting communication systems; responsive linear amplifiers, flexible filters and linear frequency translation, in addition to analogue signal processing, magnetic resonance probeheads, cell-circuit interaction and chaotic communications system implementation.